CHAPTER 20

WASTEWATER AND RECLAIMED WATER IRRIGATION

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Abstract. *Irrigation with reclaimed water from municipal wastewater treatment plants and wastewater from industrial sources is very widespread and socially acceptable. Increasingly, reclaimed water and wastewater are seen as important resources for water conservation. The design and operation of irrigation systems using these sources of water should take the constituents of the water into account. These constituents include nutrients and potential threats to human health and the environment. Nutrient balances to take the nitrogen and phosphorus content into account may be advisable. Irrigation with reclaimed water requires the use of separate distribution systems in urban environments.*

Keywords. *Human health, Irrigation systems, Nitrogen, Nutrient balance, Reclaimed water, Phosphorus, Wastewater, Water quality.*

20.1 INTRODUCTION

Irrigation with reclaimed water from municipal wastewater treatment plants and wastewater from municipal and agricultural sources is becoming more widespread and accepted. The design and operation of irrigation systems utilizing wastewater and reclaimed water has some very important differences from irrigation systems designed and operated to apply water from potable or first-use water sources. The differences arise due to the constituents of the wastewater and reclaimed water, primarily as these constituents degrade human health and the environment. The design and operation principles also apply when the irrigation source is a surface water supply with degraded quality.

The terms *reclaimed water* and *wastewater* are occasionally used interchangeably, but there are important differences. Reclaimed water has received tertiary treatment, including filtration and disinfection, from municipal wastewater treatment systems. The water is free of coliform bacteria and has biochemical or chemical oxygen demand, turbidity, and odor properties comparable to those of potable water. Wastewater has undergone primary treatment (removal of settleable and floating materials) and some secondary treatment (stabilization of most organic materials and some reduction of nutrient levels). The amount of secondary treatment will depend on the design and operation of the waste treatment system. The range is from very little secondary treatment in some single-stage lagoon systems to near-complete secondary treatment in facilities with multiple stages, which may include constructed wetlands as a final polishing stage. Wastewater may be available from agricultural waste treatment systems, municipal wastewater treatment plants, and food processing plants. Wastewater from industrial sources is not normally used for irrigation or production of reclaimed water. Wastewater will have significant organic material, characterized by biochemical or chemical oxygen demand (BOD/COD), suspended solids (SS), possibly pathogens, nutrients, and may contain other constituents of concern. Reclaimed water, in general, may be applied to areas with public access, such as parks, playgrounds, ornamental plantings, and golf courses. Wastewater, however, may not be applied to areas with public access and requires land treatment before the runoff or percolated water will meet water quality standards for primary contact and guidelines for nutrient content.

There are two general purposes for using wastewater and reclaimed water for irrigation. The first is to use the water with its nutrient content as a resource. The second is to use irrigation to treat and/or dispose of wastewater or reclaimed water in a plant-soil system. Irrigation (slow rate land application) is one of the three recommended methods of land treatment of municipal wastewater; the other two are rapid infiltration and overland flow (USEPA, 1981).

Irrigation with reclaimed water and wastewater has many advantages and disadvantages (Heaton, 1981; Lejano et al., 1992) when compared with irrigation with water from nondegraded sources. Reclamation of wastewater constitutes a new, reliable source of irrigation water. The nutrients have a positive value for crop, landscape, and turf production. Irrigation with wastewater and reclaimed water is an economical, cost effective, environmentally acceptable, and increasingly socially acceptable form of land treatment.

There are also disadvantages to using wastewater and reclaimed water for irrigation. Irrigation with wastewater and reclaimed water is regulated by national and state agencies for the protection of public health and the environment. Record keeping and monitoring may be required. Even the highest-quality reclaimed water has lower quality than potable water. The water may have elevated levels of dissolved solids, sodium, nutrients, heavy metals, organics (BOD), pathogens (bacteria, viruses, protozoa, and nematodes), trace organics, and toxic anions that require additional considerations in design, operation, and management. Design and operation of such irrigation systems are more complex than systems using other water supplies. Irrigation with reclaimed water requires the use of separate distribution and application systems, with special precautions to prevent mixing of reclaimed water and potable water supplies.

There are many examples of successful reclaimed water and wastewater irrigation systems documented in the literature (e.g., Mantovani et al., 2001, surveyed 40 reuse projects in the U.S. and 25 more in ten other countries). The Lubbock, Texas, system is an excellent example of wastewater irrigation illustrating its advantages and disadvantages. Since 1938, the Gray farm east of Lubbock has been irrigated with secondary treated municipal wastewater (George et al., 1987). Before 1982, cotton and wheat were flood or furrow irrigated with 2 to 4.5 m of wastewater each year. This overirrigation resulted in groundwater mounding beneath the farm, with a pronounced degradation of groundwater quality. Groundwater samples collected between 1980 and 1982 showed nitrate-nitrogen concentrations between 5 and 36 mg/L, COD between 27 and 125 mg/L, and total phosphorus between 0.1 and 3.5 mg/L. In 1982, the land treatment system was expanded in area with the addition of the nearby Hancock farm for wastewater irrigation, additional storage reservoirs, and center pivot irrigation systems. After system expansion, the groundwater quality improved between 1982 and 1987 in most of the 27 monitoring wells.

The Water Conserv II project in Florida is another excellent example of the use of reclaimed water in agriculture (Cross and Jackson, 1993; Parsons et al., 1995). Reclaimed municipal wastewater from Orlando and Orange County is used to irrigate over 3000 ha of citrus. In 1995, the system delivered an average of 95,000 m^3/d. The municipal wastewater receives tertiary treatment and disinfection, so it has a quality equivalent to potable water except for an unknown protozoan content and a low nutrient content. Reclaimed water is delivered at operating pressure to the property boundaries of the citrus at no cost. Reclaimed water in excess of citrus ET is disposed of in rapid-infiltration basins to recharge the Floridan aquifer. Benefits of the system are significant. Orlando and Orange County are meeting the mandate of zero discharge of municipal wastewater into surface waters, the citrus growers benefit from the pressurized free water with its nutrients, the net pumpage from the Floridan aquifer is reduced, and public attitude has shifted. The public and the growers now regard reclaimed water as a resource, rather than as a waste disposal problem (Parsons et al., 1995). An important aspect of Water Conserv II is that reclaimed water is used for sprinkler and microirrigation of a human food crop, although the crop is peeled before consumption.

20.2 CONSTITUENTS AND CHARACTERISTICS OF WASTEWATER AND RECLAIMED WATER

The quality of reclaimed water and wastewater is impacted by a wide variety of chemical, biological, and physical constituents, with a broad range of concentrations. The constituents and concentrations depend on the source waters, the nature of the industry or activity that generates the wastewater, and the type and degree of treatment, including storage, before use. Examples of concentrations for major constituents are presented in Table 20.1.

The chemical constituents of concern also include total dissolved solids (salts), dissolved gases (e.g., ammonia), ions of elements and compounds (e.g., sodium, chloride, and nitrate), heavy metals (trace elements), alkalinity, trace organic compounds, and oil and grease. Dissolved solids concentration is characterized by electrical conductivity. Sodium concentration may be characterized by the sodium adsorption ratio. Hydrogen ion activity (pH) and reduction-oxidation potential (Eh) are important chemical characterizations. Biological constituents of concern include bacteria, viruses, protozoa, helminths (nematodes, tapeworms, and roundworms), phytoplankton (primarily

Table 20.1. Examples of concentrations of constituents in wastewater and reclaimed water.

Example No.[a]	Type, Location, and Source of Degraded Water	Concentrations[b] BOD$_5$ (mg/L)	COD (mg/L)	NH_3-N (mg/L)	Total N (mg/L)	P (mg/L)	TSS (mg/L)
1	Medium-strength, untreated domestic wastewater	220	500	25	0	8	220
2	High-strength, untreated domestic wastewater	400	1000	50	85	15	350
3	Lubbock, Texas, treatment plant effluent	175		17	24	9	
4	Tallahassee, Florida, municipal holding pond effluent	12	65	2	6	7	30
5	Water Conserv II, Orange County, Florida	<5		0		5	<5
6	Design dairy concentrated animal feeding operation (CAFO) lagoon	1500	350	120	200	58	
7	Design beef CAFO runoff lagoon	1400		180	200		
8	Design swine CAFO lagoon	1200	400	220	349	76	
9	Design poultry CAFO lagoon			550	750	100	
10	Erath Co., Texas, Dairy A milking parlor		6397	248	260	85	2884
11	Erath Co., Texas, Dairy A primary lagoon		1480	161	172	53	839
12	Erath Co., Texas, Dairy A second stage lagoon		650	117	117	39	480
13	Erath Co,. Texas, Dairy B primary lagoon		5467	267	282	55	2333
14	Piedmont Region, South Carolina, swine lagoon effluent		1500	80	175	80	
15	Paris, Texas, soup processing wastewater overland flow system	550	1190	0.7	28	6	795
16	California wine processing	950			33		288
17	Ohio coffee processing	1145	3148	91	186	12	960
18	Washington vegetable processing	1440	2190		30	9	690
19	United Kingdom meat processing		1900	30	115	15	640

(continued)

Table 20.1 continued.

[a] Sources of values for the examples 1 - 19.

1.-2. USEPA, 1981 and Tchobanoglous and Burton, 1991
3. George et al., 1987
4. Overman and Schanze, 1985
5. Cross and Jackson, 1993
6.-9. SCS, 1992
10.-13. Sweeten and Wolfe, 1994
14. Hegg et al., 1984
15. Tedaldi and Loehr, 1992
16. Crites, 1987
17. Loehr et al., 1988
18. Jones et al., 1993
19. Russell et al., 1993

[b] BOD_5 is biological oxygen demand, five-day method; COD is chemical oxygen demand; NH_3-N is ammonia nitrogen; total N is total nitrogen; P is phosphorus, and TSS is total suspended solids.

algae), zooplankton, and organic matter. Organic compounds that require oxygen for microbial degradation are characterized by biochemical oxygen demand (BOD) or chemical oxygen demand (COD). The physical characteristics of wastewater are typically described by suspended solids, settleable solids, color, clarity, odor, and temperature. This section briefly discusses the constituents of interest in wastewater irrigation and slow rate land treatment of wastewater. More complete descriptions are contained in Tchobanoglous and Burton, 1991; Greenberg et al., 1992; USEPA, 1981; Reed et al., 1988; and USGA, 1994. The standard methods for determination of the presence, characterizations, and concentration of all constituents are published in Standard Methods for the Examination of Water and Wastewater (Greenberg et al., 1992).

The chemical constituents of concern also include total dissolved solids (salts), dissolved gases (e.g., ammonia), ions of elements and compounds (e.g., sodium, chloride, and nitrate), heavy metals (trace elements), alkalinity, trace organic compounds, and oil and grease. Dissolved solids concentration is characterized by electrical conductivity. Sodium concentration may be characterized by the sodium adsorption ratio. Hydrogen ion activity (pH) and reduction-oxidation potential (Eh) are important chemical characterizations. Biological constituents of concern include bacteria, viruses, protozoa, helminths (nematodes, tapeworms, and roundworms), phytoplankton (primarily algae), zooplankton, and organic matter. Organic compounds that require oxygen for microbial degradation are characterized by biochemical oxygen demand (BOD) or chemical oxygen demand (COD). The physical characteristics of wastewater are typically described by suspended solids, settleable solids, color, clarity, odor, and temperature. This section briefly discusses the constituents of interest in wastewater irrigation and slow rate land treatment of wastewater. More complete descriptions are contained in Tchobanoglous and Burton, 1991; Greenberg et al., 1992; USEPA, 1981; Reed et al., 1988; and USGA, 1994. The standard methods for determination of the presence, characterizations, and concentration of all constituents are published in Standard Methods for the Examination of Water and Wastewater (Greenberg et al., 1992).

20.2.1 Chemical Constituents and Characteristics

Nitrate-nitrogen (NO_3-N) and phosphates (PO_4 species) are the primary chemical anions of concern in wastewater and reclaimed water. Nitrate in water consumed by very young infant humans interferes with the ability of hemoglobin in blood to transport oxygen (NAS, 1978). The name of the disease is methemoglobinemia (blue baby syndrome). To avoid this disease, the USEPA has established a drinking water standard of 10 mg NO_3-N/L. Nitrates are also toxic to animals when there are high levels in forage. Nitrates contribute to the eutrophication of surface water. Ammonia and nitrite are toxic in certain circumstances to plants and animals, including humans. Phosphorus is usually the limiting nutrient in surface water bodies, so is frequently associated with eutrophication. When the P levels become high, especially relative to organic carbon and N, algal blooms will significantly change the biological and chemical composition of a surface water body.

20.2.1.1 Nitrogen. Nitrogen forms in wastewater may be reported as NO_3-N, ammonia, organic N, and total Kjeldahl nitrogen (TKN). Ammonia (NH_3) and the ammonium ion (NH_4^+) exist in aqueous solutions in an equilibrium that is highly pH dependent. As the pH increases above 7, the relative proportion of ammonia increases exponentially. Organic N is defined functionally as the organically bound N in the tri-negative oxidation state, so does not include all organic N compounds. Organic N includes proteins, peptides, nucleic acids and urea, and various synthetic organic materials. TKN is a term that reflects the method for the determination of organic N and ammonia in one analytical method. Nitrite, NO_2^-, is an intermediate oxidation state of N, both in the oxidation of ammonium to nitrate and in the reduction of nitrate.

20.2.1.2 Phosphorus. Phosphorus (P) compounds are classified as orthophosphates, condensed phosphates (the polyphosphates), and organically bound phosphates. Phosphates that respond to colorimetric tests without preliminary hydrolysis or oxidative digestion of the sample are termed reactive P, which is largely a measure of orthophosphate concentration. Condensed phosphate or acid-hydrolyzable P is the fraction produced by acid hydrolysis at boiling water temperature. Organically bound P is the fraction that is converted to orthophosphate only by oxidative destruction of the organic matter in the sample. Total P is the sum of the reactive, acid-hydrolyzable, and organic P. The various forms of P occur in solution, in particles or detritus, or in the bodies of aquatic organisms. Some phosphates are still used in commercial cleaning preparations and in treatment of boiler waters. Organic phosphates are formed by biological processes and are contributed to wastewater in fecal material, plant residues, and food residues.

20.2.1.3 Carbon. Total carbon in wastewater is composed of inorganic carbon [carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and dissolved carbon dioxide] and organic carbon. Total organic carbon (TOC) is used to describe the degradable organic material in wastewater. The organic carbon in water and wastewater is composed of a variety of organic compounds in various oxidation states. BOD and COD are used to characterize the fractions that can be oxidized by biological or chemical processes. The presence of organic carbon that does not respond to either of these tests makes these tests unsuitable for the measurement of the total organic carbon. Total organic carbon is independent of the oxidation state of the organic matter and does not measure other organically bound elements, such as nitrogen and hydrogen, nor the inorganics that can contribute to the oxygen demand measured in the BOD and COD tests. The tests for TOC are based on the breakdown of the organic molecules into single-carbon units that are converted to a single molecular form (carbon dioxide) that can be measured quantitatively.

20.2.1.4 Oil and grease. Oil and grease concentrations in wastewater are defined by the amount extracted by a given solvent (usually trichlorotrifluorethane), as opposed to an absolute quantity of a specific substance. Most substances in the oil and grease group are mineral hydrocarbons and biological lipids. This includes fatty matter from animal and vegetable sources and hydrocarbons of petroleum origin. The oil and grease group also includes non-volatilized substances extracted by the solvent from an acidified sample. These substances include chlorophyll, sulfur compounds, and certain organic dyes. Oil can reduce germination of seeds and reduce crop yields when applied at high rates. Grease will reduce soil permeability and have an adverse impact on soil microorganisms (Ritter, 1987). Oil and grease are most likely to occur in wastewater from food processing operations, especially meat packing and poultry. Poultry processing wastewater may have 170 to 230 mg/L oil and grease (Ritter, 1987).

20.2.1.5. Boron. Boron concentrations in municipal wastewater will be higher than the source water concentrations as a result of the boron content of household and commercial detergents. Typical boron levels will be from less than 0.1 mg/L to over 4 mg/L. The maximum recommended application level of boron in irrigation is 2.0 mg/L (see Chapter 7). Boron is an anion, so is not held by the soil exchange sites, but borates are moderately held by soil cation exchange sites. Boron is reported to be more difficult to leach than other anions, requiring twice as much leaching water (Peacock, 1994). Boron toxicity is most pronounced in tree crops and is manifested by tip and marginal burning of the leaves. Boron toxicity will not ordinarily show in turfgrasses because the boron that accumulates is removed by frequent mowing.

20.2.1.6. Other ions. Determination of the common anions such as bromide, chloride, fluoride, nitrate, phosphate, and sulfate are desirable to characterize a water and to assess the need for a specific treatment. Ion chromatography is typically used to determine the anions present in the water sample. The concentrations of sodium, calcium, and magnesium ions are needed for calculation of the sodium adsorption ratio (SAR). Knowledge of the salinity and SAR of irrigation water from any source is necessary due to the adverse impacts of high SAR on soil properties. Chloride may be phytotoxic when applied to the foliage of certain plants. Corrosion of dissimilar metals in irrigation systems is increased when the wastewater has a high salinity, because of the increased electrical conductivity of the water. Anodized pipe, avoidance of dissimilar metals, and impressed voltage systems may be needed (Tchobanoglous and Burton, 1991; Fox and Nuss, 1987).

Detailed information on salinity, SAR, specific anion, and specific cation effects on plants and soils is contained in other sections of this book (particularly in Chapter 7) and in Tanji (1990). Salinity in wastewater will originate from source water salinity, concentrations through recycling (e.g., use of effluent as flush water), concentration from evaporation of wastewater, and from concentrated animal feeding operations (CAFOs). Specific ions originate from certain food processing operations. Caustic peeling processes for peaches and potatoes, for example, may result in high sodium in the wastewater; sugar processing wastewater may contain high levels of sulfur; seafood processing wastewater may contain high nitrate and sodium levels (Ritter 1987); and high-strength CAFO wastewater will have high salinity, chloride, sodium, ammonium, and orthophosphate concentrations (Sweeten and Wolfe, 1994).

20.2.1.7 Heavy metals. Heavy metals (also known as trace metals or trace elements) are of concern in wastewaters because they may accumulate in the food chain to a toxic concentration and may move through the soil into groundwater (USEPA, 1981). Heavy metals are present in low concentrations in municipal wastes that have minimal industrial components and in food processing wastes. Wastewater from animal industries will have low concentrations of copper and iron and perhaps other metals from feed additives or antibiotics, but these should be of relatively low concentrations and not normally a concern in land application. In wastewater, heavy metals tend to form metal hydroxides, phosphates, carbonates, and other precipitates that adsorb to organic solids or precipitate with other constituents (Page and Chang, 1981). These have low solubility and will be effectively filtered by the soil particles. As cations, heavy metals are held on the soil cation exchange sites, so do not move readily in the soil profile (Ritter, 1987; McBride, 1994).

Heavy metal cations, unlike sodium, calcium, magnesium, and potassium cations, do not readily participate in cation exchange due to their typically low concentrations. Plant uptake will occur, however, only when the metals are present in soluble or exchangeable form. Generally this occurs when the soil cation exchange sites are occupied and when the soil pH is less than 6.5 (USEPA, 1981). At the application rates usually encountered, soils have an adsorption capacity for heavy metals at least equivalent to that for phosphorus sorption. When heavy metals are taken up by plants, most metals will cause visible plant symptoms or plant death before the metal concentration in the foliage is toxic to animals or humans. Cadmium, copper, and molybdenum are exceptions in that toxic concentrations may build up in plant tissues before plant symptoms are present.

Cadmium is toxic to animals, humans, and aquatic life forms at concentrations as low as 15 mg/L and is a carcinogen. Cadmium may enter water through industrial discharges or the deterioration of galvanized pipe, where cadmium is an impurity of the zinc. Copper, molybdenum, nickel, lead, and zinc are other heavy metals that may be present in wastewater. Copper is toxic to plants at concentrations of 0.1 to 1.0 mg/L and can be toxic to ruminants, especially sheep, but is not a health hazard to humans. Molybdenum is not toxic in soils and water at normal concentrations, but may be toxic to animals at 10 to 20 mg/L in forage that is low in copper. Nickel is toxic to a number of plants at concentrations of 0.5 to 1.0 mg/L. Zinc is an essential nutrient, but is also toxic to many plants in varying concentrations. Phytotoxicities are more common in acid than in alkaline soils. Lead is a serious toxin that accumulates in human body tissues. Lead in water may come from dissolution of old lead plumbing or from soldered pipe joints in contact with softened, acidic water. Lead is highly immobile in the soil, however, and is unlikely to be absorbed by plants (Ritter, 1987). Other heavy metals may be of concern if industrial wastewater is used for land treatment.

Metal presence and concentrations are determined by atomic absorption and other methods.

20.2.1.8. Other chemical characteristics. Alkalinity of water refers to its acid-neutralizing capacity. It is the sum of all titratable bases, so is an aggregate property of water. Alkalinity is primarily a function of the carbonate, bicarbonate, and hydroxide content, although it may also include contributions from borates, phosphates, silicates, or other bases.

The acidity of water refers to its quantitative capacity to react with a strong base to a designated pH. Acidity is a measure of an aggregate property of water and can be interpreted only when the chemical composition of the sample is known. Acidity contributes to the corrosiveness and influences chemical reaction rates, chemical speciation, and biological processes. Acidity is determined by titration to an end-point pH.

Oxidation and reduction reactions (redox) mediate the behavior of many chemical constituents in wastewaters as well as most aquatic compartments of the environment. The reactivities and mobilities of important elements in biological systems depend strongly on redox conditions. Reactions of both electrons and protons are pH and Eh dependent. Like pH, Eh represents an intensity factor, but does not characterize the capacity for oxidation or reduction.

20.2.2 Biological Constituents and Characteristics

20.2.2.1 Pathogens. Pathogenic organisms are present in all wastewater, and should be regarded as present in all surface waters. Pathogenic organisms in wastewater are described in Section 20.4.1.

20.2.2.2 Organic matter. Wastewater that has not received full tertiary treatment will contain organic matter. The standard indicators of organic matter content are BOD, COD, and TOC, which have been mentioned previously.

20.2.2.3 Oxygen demand. The BOD and COD determinations are empirical tests to measure the relative oxygen requirements of wastewaters, effluent, and polluted waters. Biochemical oxygen demand is the amount of dissolved oxygen required to meet the metabolic needs of microorganisms that degrade carbonaceous organic material in a water sample (Loehr et al., 1979) and is used as an indirect measure of the biodegradable organic concentration of the sample. The BOD test also includes the oxygen used to oxidize inorganic matter such as sulfides and ferrous iron. Tchobanoglous and Burton (1991) provide details of the laboratory tests, limitations, and reaction kinetics of BOD determination.

COD is a quantitative measure of the amount of oxygen required for the strong chemical oxidation of organic carbonaceous material. Ammonia is not oxidized unless there is a significant concentration of chloride ions. The COD of a waste is generally higher than the BOD because more compounds can be chemically oxidized than biologically oxidized (Tchobanoglous and Burton, 1991).

20.2.2.4 Trace organics. Trace organic compounds such as pesticides and other agricultural chemicals may be toxic and may be significant contaminants of wastewaters. Most trace organics are effectively removed by soil treatment. Trace organics such as herbicides are adsorbed, followed by biodegradation and volatilization. Plant uptake may occur as a function of solubility, size, concentration, and polarity of the organic molecule; the organic matter content, pH, and microbial activity of the soil; and the climate (USEPA, 1981; Hutchins et al., 1985). It is unlikely that crop uptake of trace organics is sufficient to pose a threat to animals or humans (USEPA, 1981).

20.2.2.5 Microorganisms. As a consequence of the nutrient content of wastewater, any storage of wastewater and reclaimed water prior to irrigation will result in active growth of phytoplankton and other microorganisms. The major microorganisms of concern in irrigation water supplies are those, such as algae, slime bacteria, and colonial protozoa, that affect physical and chemical water quality.

20.2.3 Physical Constituents and Characteristics

Physical properties of water include odor, dissolved oxygen, solids, color, and turbidity. Turbidity is caused by suspended mineral matter, finely divided organic and inorganic matter, soluble colored organic compounds, phytoplankton, and zooplankton. Turbidity is generally reported in nephelometric turbidity units (NTU). Color is the true color of the water, after turbidity has been removed.

20.2.3.1 Odor. Odor is characterized by its intensity and hedonic tone (the pleasantness or unpleasantness), and character or quality, which are usually described with words that indicate a likely source (Dravnieks, 1979). Offensiveness is a combination of intensity and hedonic tone as well as duration and frequency. Odor is a common problem with wastewater treatment and application. In general, the more complete the wastewater treatment, the fewer problems there will be with odor. Irrigation of wastewater in land application systems requires application with only minimal offensive odor.

20.2.3.2 Dissolved oxygen. Dissolved oxygen (DO) is essential to the biological and chemical degradation of the carbonaceous and nitrogenous organic material in wastewater. If the DO is insufficient to meet the oxygen needs of the organic matter, the receiving water body will be anaerobic except perhaps for a very thin surface layer. Nearly all aquatic organisms, with the exception of anaerobic bacteria, must have free oxygen for respiration to survive (Wheaton, 1977).

20.2.3.3 Solids. Solids refer to matter suspended or dissolved in water or wastewater. Solids may adversely affect wastewater quality in a number of ways. Total solids are quantified by the amount of material residue left in a vessel after evaporation and subsequent drying in an oven at a defined temperature. Total suspended solids (TSS) are the solids removed by a filter (2.0 µm or smaller nominal pore size). Fixed solids is the term applied to the residue of total suspended and dissolved solids after heating for a specified time and temperature. The weight loss is a measure of the volatile solids.

20.2.4 Quality of Selected Wastewater and Reclaimed Water

20.2.4.1 Municipal. Municipal wastewater may be characterized as low, medium, and high strength (Tchobanoglous and Burton, 1991) based on the concentrations of the constituents of greatest concern (Table 20.1).

20.2.4.2 Concentrated animal feeding operations (CAFOs). Dairy lagoon effluent will have a wide variation in strength as a consequence of the source of the wastes, the dilution by milking parlor washwater and rainfall, and the concentration by evaporation in the open lots and in the waste treatment system. Sources of wastes may include any combination of milking center wastes, holding shed wastes, scraped feed lane wastes, and open lot runoff (SCS, 1992; Sweeten and Wolfe, 1994). Water use per cow per day in the milking center may range from about 20 L to over 550 L if fresh water is used for flushing of manure (SCS, 1992). Where fresh water is limited, dairy producers use lagoon effluent for flushing manure from feed lanes. Wastewater from beef, poultry, and swine CAFOs will have similar variations in strength.

20.2.4.3 Food processing wastes. Wastewater from the wine industry (Table 20.1) is characterized by low pH, low nutrients, and a relatively high BOD (Crites, 1987). Raw wastewater from the Campbell Soup Company in Paris, Texas, is characterized by low nitrogen and phosphorus, but relatively high oil and grease (125 mg/L) and oxygen demand. Food processing wastewaters are extremely variable in content and level of treatment.

20.3 NUTRIENTS IN WASTEWATER AND RECLAIMED WATER

Nitrogen (N) and phosphorus (P) are plant nutrients that may be managed as resources or as potential contaminants that must be removed by soil-plant systems in the land treatment process. If a reservoir is to be used with the irrigation system, the major concern with nitrogen and phosphorus as nutrients is their effect on the trophic level of surface water. Concentrations of 0.3 mg/L inorganic N and 0.02 mg/L inorganic P have been identified as the critical thresholds for promotion of algae and aquatic macrophytes in lakes (Loehr et al., 1980; Daniel et al., 1993).

Phosphorus is the single most limiting nutrient for eutrophication, although N may be the limiting nutrient in waters containing more than 0.03 mg/L dissolved P or when the total N to total P ratio is less than 15:1 (Daniel et al., 1993). Municipal wastewater and animal agricultural wastewater normally have total N to total P ratios of much less than 15:1, typically less than 5:1 (see Table 20.1). In soils, a N:P ratio of about 7:1 is considered ideal for uptake by plants (Bowmer and Laut, 1992).

The irrigation or environmental engineer should be cognizant of basic nitrogen and phosphorus forms in wastewater and reclaimed water. The nitrogen form and content will vary considerably, depending on the treatment before irrigation. Nitrogen and phosphorus losses will occur in the treatment ponds and storage reservoirs as a function of water chemistry, biology, and environmental conditions.

Nitrogen in wastewaters is normally in the organic nitrogen and ammonium-ammonia forms. The nitrate content of anaerobically treated wastewaters will ordinarily be very low. In decomposition of organic wastes, the oxygen demand for the microbial metabolism is satisfied first from the available dissolved oxygen. Nitrates are the next source of oxygen, so any nitrate in the system is then reduced to ammonium. When the wastewater is applied to an aerobic plant-soil environment, bacteria nitrify the ammonium to nitrite as an intermediate state, then to nitrate. Nitrate is highly mobile in soil water, but ammonium is not. Ammonium is adsorbed to negative charge sites on clay minerals, with an adsorption capacity sufficient to retain all ammonium from slow rate (irrigation) applications (Broadbent and Reisenaur, 1985).

Biological transformations of nitrogen are immobilization, mineralization, nitrification, denitrification, and nitrogen fixation by plants (Keeney, 1983). Immobilization refers to the conversion of inorganic forms to organic compounds. Mineralization is the conversion of organic nitrogen to ammonium. Plant uptake of inorganic nitrogen (nitrate and ammonium) and incorporation into organic plant components is the primary immobilization process.

The phosphorus content of wastewater, like nitrogen, will also vary significantly as a function of the source and type of treatment. The phosphorus content of the wastewater to be used for irrigation should be determined.

Phosphorus exists in several forms in water and the soil-plant environment. Particulate P is composed of organic material, crystalline minerals, amorphous precipitates, and reactive phosphorus (primarily orthophosphates) sorbed to soil particles, primarily clays. It should be noted that the orthophosphates are anions, so they do not participate in cation exchange and are not adsorbed to the clay mineral sites with negative charge potentials. The phosphorus minerals and precipitates have varying solubility and are generally reaction products with calcium, iron, and aluminum. Soluble P is composed of orthophosphates (PO_4^{3-}, HPO_4^{2-}, and $H_2PO_4^{-}$), polyphosphate (P_2O_7), and soluble organic compounds. The distinction between particulate and soluble is somewhat arbitrary, because the separation is based on the diameter of the filter pores (0.45 µm). Phosphorus soil and aquatic chemistry is complex; additional information is contained in Diaz et al. (1994), McBride (1994), and Stumm and Morgan (1996).

In a soil solution, an equilibrium is established between the phosphorus in solution and the labile phosphorus on soil particle surfaces. As plants remove phosphate from the soil water, the equilibrium is restored. The soluble P, especially orthophosphate, will move with soil water and will equilibrate with labile phosphorus. Conventional wisdom is that a soil will not have a leachate with a significant P concentration. In general, this is true, especially with a tilled, row-crop soil with a moderate to high P-sorption capacity. Phosphorus profiles in soils receiving animal wastewater or solid wastes typically show an exponential decrease in concentration with depth (Sharpley et al., 1984; Allhands et al., 1995). In addition to the conventional soil fertility tests, bioavailability tests may be used to provide additional management information (Sharpley and Withers, 1994).

20.4 HEALTH CONCERNS

Pathogenic microorganisms, including bacteria, viruses, and protozoa, are present in human and animal wastes and the waters containing these wastes (NRC, 1998). There is no doubt that irrigation of food crops with sewage or treated wastewater contaminated with sewage results in increased disease occurrence (Rosas et al., 1984; Rose, 1986; Ali, 1987) or that the potential exists for disease transmission from irrigation of public use areas and food crops with wastewater. The National Research Council (NRC, 1996) concluded that food crops irrigated with reclaimed water do not present a greater risk to consumers than do crops irrigated from conventional sources. The essential elements to protect human health are adherence to state standards for reclaimed water, site restrictions, and good system reliability.

Pathogens could be transmitted to humans by ingestion of the wastewater, inhalation of aerosols from the wastewater, self-inoculation or contamination of foods or liquids after direct contact, contamination of food or animal feed, and contamination of potable water supplies. For a disease to occur from wastewater irrigation, the pathogen would have to survive any treatment process, persist in the environment, and be present in sufficient numbers to cause the disease in a susceptible individual (Rose, 1986). Health and safety are the overriding concerns when treated wastewater is applied to public areas, food crops, and forage systems. Although disease transmission by irrigation of treated wastewater (not contaminated with raw sewage) has not been documented as a problem (Rose, 1986), contaminated water from wastewater treatment plants and/or animal operations has been implicated in disease outbreaks (e.g., MacKenzie et al., 1994).

For irrigation of public areas with municipal wastewater, state departments of health generally do not accept any risk above that of irrigation with potable water. The biological quality standard is water that is essentially bacteria and virus free (Asano et al., 1992). Most major municipal reclaimed wastewater projects produce water with residual chlorine of 1 mg/L. Examples are Colorado Springs, Colorado (Schwebach et al., 1988), Orlando, Florida (Cross and Jackson, 1993), Monterey, California (Sheikh et al., 1990), and San Diego, California (Shamloufard et al., 1995). Irrigation of agricultural crops with municipal wastewater is done with water that has at least secondary treatment. The Muskegon County, Michigan (Brenner et al., 1988), and Lubbock, Texas (Moore et al., 1988), projects are examples.

Wastewater irrigation should be considered to have the potential for pathogen transmission. The information on biological quality of the water or associated epidemiology is not well understood enough to develop standards. There is no evidence that regulations or standards are needed, but there is sufficient information to indicate that considerable caution and adherence to recommended practices are essential to protect human health.

Quality of wastewater applied to forage crops may be a concern in the food processing industry. Applying animal wastes to forage crops to be ensiled may result in the introduction of several bacteria species such as *Bacillus* and *Clostridium* (Ostling and Lindgren, 1991). The spores of *Clostridium* will survive in the silage. Therefore, *Clostridium* may have an adverse effect on the ensiling process and result in poor silage and reduced animal performance, whereas *Bacillus* may encourage aerobic deterioration of silage when removed from the silo and fed. If the spores enter the milk through contamination and if the milk is used in making cheese, "blowing" (production of butyric acid and gas) of hard cheeses may result (Jonsson, 1991).

E. coli is the most frequent species found in animal manure, but populations decline drastically one week after waste application to growing forage (Rammer et al., 1994). Animal wastes may also be a source of *Listeria monocytogenes* (Husu et al., 1990) and consumption of raw vegetables contaminated with *Listeria* from untreated animal wastes may cause listeriosis, a potentially fatal disease.

20.4.1 Biological Organisms Found in Wastewater

The important biological constituents of wastewater are algae, bacteria, viruses, protozoa, and helminths. Virtually all wastewater without tertiary treatment contains pathogenic organisms that can produce disease in humans. Pathogenic protozoan oocysts and cysts may be present even in treated wastewater that has 1 mg/L residual chlorine. Additional information is contained in Rose (1986) and Shuval et al. (1986). Information on algae is contained in Goldman et al. (1972), Reddy (1981), Vymazal (1995), and Stumm and Morgan (1996).

20.4.1.1 Bacteria. The most significant pathogenic bacteria cause diseases such as dysentery (*Shigella*), typhoid, and gastroenteritis, which is generally caused by *Salmonella, Campylobacter,* and certain types of *E. coli* (Rose, 1986). These species inhabit the intestinal tracts of humans and other mammals. *Salmonella* species are especially common in cattle feces (Thelin and Gifford, 1983) and human waste (Rose, 1986).

The bacterial quality of wastewater is assessed with indicator bacteria that may not be pathogenic. Indicator bacteria are used because they are present in wastewater in greater numbers than pathogenic bacteria, they are easier to isolate, and they are safer to handle (Thelin and Gifford, 1983). If indicator bacteria are present in a water sample, the presence of pathogenic bacteria is assumed. Indicators of bacterial quality of water are total coliform (TC), fecal coliform (FC), and fecal streptococci (FS). Both FC and FS are present in the feces of humans, and domestic livestock and poultry. Several procedures for determination of the TC, FC, and FS bacteria concentrations have been published (e.g., Niemi and Niemi, 1991; Sherer et al., 1992).

20.4.1.2 Viruses. Enteroviruses that can be transmitted in water include poliovirus, echo, hepatitis A, and coxsackie (Rose, 1986). Norwalk, rotavirus, and other viruses capable of producing infection may also be present in wastewater (Rose, 1986; Ward et al., 1989). Rose (1986) states that the presence of viruses in wastewater causes concern because there is a dearth of information on the occurrence and significance of viruses; detection methods may recover less than 50% of the viruses in a sample; the survival of enteric viruses in the environment is not well known and viruses may not be removed efficiently in treatment systems; small numbers of viruses could cause an infection; and the bacterial indicator system is not always reflective of the presence of viruses.

Secondary and tertiary treatment of wastewater removes viruses with an efficiency of 90% to 99%, but some viruses will be present following disinfection (Rose, 1986). It is suspected that viruses, when aerosolized from spray irrigation, may be more resistant to environmental conditions than bacteria (Rose, 1986). Wastewater treatment ponds and storage reservoirs have a marked impact on virus survivability (Ward and Irving, 1987). Reductions of one to two logs in virus counts were reported in the Lubbock study (Moore et al., 1988; Ward et al., 1989). Under favorable conditions, viruses can survive on vegetable surfaces for over two months. Low temperatures, high humidity, presence of organic matter, and shading from direct sunlight protect against desiccation and favor virus persistence (Ward and Irving, 1987). Viruses die rapidly in a warm and dry environment. Virus survivability in the process of aerosolization and in aerosol form is thought to be low (Schwebach et al., 1988).

20.4.1.3 Helminths. Parasitic nematodes, roundworms, hookworms, tapeworms, and whipworms are endemic in wastewater in areas of the world with poor hygiene (Rose, 1986). The ova from these parasitic worms aid in their survival in wastewater. The ova are generally resistant to chlorine, but settle out during sedimentation. High rate algal ponds (shallow treatment ponds specifically designed to have a high algal population for daytime oxygen production to reduce oxygen demand of the wastewater) and waste stabilization ponds are fairly effective in the removal of helminth ova (Ayres et al., 1992). *Ascaris lumbricoides* (roundworm) ova are the most resistant of these enteric pathogens, so are often used as indicators of parasites (Rose, 1986; El Hamouri et al., 1994). The World Health Organization (1989, cited in Ayres et al., 1992) recommends a maximum of one human intestinal nematode egg per liter for irrigation.

20.4.1.4 Protozoa. *Giardia lamblia* and *G. muris* are parasitic protozoa that cause diarrhea in humans who ingest their cysts. *Giardia* cysts should be presumed to be in all wastewater and surface waters used for irrigation (LeChavallier et al., 1991). Precautions to avoid infection are the same as for *Cryptosporidium*, which is a more significant threat in wastewater irrigation. *C. parvum* is the parasitic protozoa that was responsible for the outbreak of severe diarrhea and related symptoms (cryptosporidiosis) in Milwaukee, Wisconsin, in the spring of 1993 (MacKenzie et al., 1994).

The prevalence of *C. parvum* oocysts in wastewaters from all sources, especially those from dairy and dairy calf industries, indicates the need for caution and protective measures when using wastewater for irrigation. A need for reasonable precautions is also indicated for irrigation with surface water from agricultural and urban watersheds (Ongerth and Stibbs, 1987; Hansen and Ongerth, 1991; LeChevallier et al., 1991).

20.4.2. Health Aspects of Irrigation with Wastewater

A five-year study of the Monterey, California, wastewater reclamation project indicated that the use of tertiary treated wastewater (reclaimed water) for food crop irrigation is safe and acceptable (Sheikh et al., 1990). The food crops were artichokes, celery, broccoli, lettuce, and cauliflower.

In Colorado Springs, Colorado, tertiary treated municipal wastewater is used for irrigation of public park areas (Schwebach et al., 1988; Durand and Schwebach, 1989). The tertiary treatment consists of filtration and chlorination of effluent from the wastewater treatment plant. The city also uses urban mountain runoff water, without treatment, for irrigation of public park areas. An epidemiological study was conducted to examine the gastrointestinal illness levels associated with irrigation with different water qualities. The conclusion of the Colorado Springs epidemiological study was that there was no difference in self-reported gastrointestinal illness rates between park visitors in parks irrigated with potable water compared with those in parks irrigated with treated wastewater. “Wet grass conditions” from any source of water were associated with a statistically significant increase in self-reported gastrointestinal illness. The correlation was even stronger when the irrigation water FC or FS counts were above 500/100 mL. The authors hypothesized that endotoxins from living or dead enterobacteria are ubiquitous to the grass and are transferred to people from the wet grass.

Several epidemiological studies of health risk as a result of wastewater irrigation have been conducted in Israel, where 70% of the urban wastewater flow of the nation is used as a water resource for irrigation (Shuval et al., 1989). Most of the wastewater receives primary treatment and secondary treatment in stabilization ponds. Shuval et al. (1989) conducted a study of irrigation workers, their families, and the general population in 20 agricultural settlements. The quality of the irrigation wastewater was poor, with coliform counts of 10^4 to 10^5/100 mL. The authors concluded that enteric disease levels were no higher in wastewater workers, their families, and people who may have been in contact with irrigation aerosols than in the general population. The studies did note that low levels of bacteria and viruses of wastewater origin were found at distances up to 730 m downwind from an irrigated field.

The Lubbock infection surveillance survey (LISS), an epidemiological study of the health risk associated with wastewater irrigation, was conducted from 1980 to 1983 (Moore et al., 1988; Ward et al., 1989). Municipal wastewater from two trickling-filter plants from the city of Lubbock, Texas, was applied to agricultural crops. The wastewater was piped to a 1153-ha farm for irrigation, primarily through 22 center pivot systems. In 1982, the wastewater was pumped directly to the pivots. In 1983, playas (shallow, natural water-filled depressions, usually with no external drainage) were used as wastewater storage reservoirs prior to irrigation. In the spring of 1982, the average concentrations for FC were 4.3×10^6 cfu/100 mL (cfu is colony-forming units), whereas the 1983 spring concentrations were 5.2×10^3 cfu/100 mL. All levels exceeded the EPA guidelines of 1000 FC/100 mL for this irrigation. The enterovirus concentrations were 40 pfu/100 mL for spring 1982 and 2 pfu/100 mL for spring 1983 (pfu is plaque-forming units). Ward et al. (1989) concluded that exposure to wastewater aerosols in the LISS was not correlated with an increase in disease incidence, but there was an indication that new viral infections occurred more frequently in people with high exposure than in people with moderate or low exposure. There was no evidence that wastewater spray irrigation caused increased rotavirus infection, but spread of other viral infections may have occurred (Ward et al., 1989).

20.5 CROPS SUITABLE FOR IRRIGATION WITH WASTEWATER AND RECLAIMED WATER

Consideration must be given to the crop when irrigating with wastewater or reclaimed water. If disposal of the water and/or nitrogen content is the primary consideration, crop selection for land application sites may be based either on water disposal or utilization or nitrogen removal. For water use, maximum ET rates throughout the growing season are desired. The crop may or may not be harvested and removed. For N removal, crop selection should be based on the total N removed, which is a function of the crop yield removed from the field and the N content of that yield. Land application systems are not usually designed based on phosphorus loading as a limiting factor. The P uptake by most cropping systems will be low relative to the P input from wastewater, especially if the system is designed to remove N from CAFO systems. If P is applied at rates in excess of the crop uptake and removal, the P sorption capacity of the soil profile should be determined and used to calculate the number of years the application site may be used for wastewater application.

Characteristics of crops selected for land treatment sites are (USEPA, 1981; George et al., 1985): high nutrient uptake and removal; high crop ET; tolerance to high soil moisture conditions; revenue or local crop use potential; suitable for equipment, labor, and management system of producer; adaptation to climate and soil; satisfaction of irrigation water quality requirements; restrictions based on use of crops for human consumption; and goodness of fit into overall operation of producer.

Virtually any locally adapted crop, including horticultural crops, may be produced with reclaimed water or wastewater without adversely affecting the quality or quantity of the crop. Kirkham (1986) summarized problems associated with the use of wastewater for vegetable crops. She concluded that apparently few problems are associated with secondary effluent applied to vegetables. If nutrient removal is a primary objective of the land treatment system, forage crops are normally selected. Most forage crops have a high ET throughout the growing season, have high nutrient requirements, are tolerant of poor drainage and/or periodic flooding, are tolerant of high salinity, and can be interseeded or interplanted with a mix of warm-season and cool-season species to extend the growing season. Perennial forage crops have a contiguous root system, whereas an annual row crop will have areas of soil without plant root systems for nitrogen uptake for significant periods in the spring. Forages also have low cultural requirements (e.g., pest management, cultivation and tillage, and critical timing of phenologically based cultural practices). In addition, forages normally have a local market or can be used in the animal agriculture operation that produces the wastewater. Barnes et al. (1995) present climatic adaptability, yields, response to fertilization, and other information for various forages.

Row crops may have high yields, but may have two disadvantages. The period in the spring before the crop begins to grow and the period after harvest are known to be times with maximum potential for nitrate leaching. Secondly, if only a portion of the crop is removed at harvest (e.g., grain), most nutrients remain in the field.

Turfgrasses that will have direct human contact may be sprinkler irrigated with reclaimed water, but not wastewater, due to wastewater quality not meeting primary contact standards. Consequently, turfgrass systems in urban and residential settings are used more for beneficial reuse of reclaimed water than for water treatment and water disposal.

Woodlands and forests are acceptable for wastewater land treatment. The advantages are minimal site maintenance, high organic content of surface litter and soil, and a stable soil profile. Older forests without understory are not suitable for nutrient removal, however (Burton and King, 1981).

20.6 DESIGN OF NITROGEN LOADING RATE

For almost all systems for application of reclaimed water or wastewater, either the hydraulic loading rate or the N loading rate will be the limiting factor. If the wastewater or reclaimed water has a relatively low N content, the determination of the total land area to irrigate and the design of the system are in accordance with the other chapters of this book. The design procedure will be altered slightly, however, because the starting point will be the volume or flow rate of water available for irrigation. If the total N content of the wastewater is high—more than about 10 mg/L, which is the case for most agricultural wastewater—the N loading rate may be the limiting factor in the system design. Both the hydraulic loading rate and the N loading rate should be compared to determine which is limiting. The hydraulic loading rate will be ET based, in accordance with other chapters. The N loading rate may be calculated with the use of a simplified annual N balance.

20.6.1 Design Procedure

The design procedure is to start with the N content and the volume or flow rate of the wastewater. Calculation of the total N balance is required to determine the area of land required for irrigation for land treatment. Sufficient land must be available for irrigation and/or land treatment without surface runoff or percolation containing more than 10 mg/L NO_3-N. The design procedure is:

1. Estimate the mean annual total N content (mg/L) of the wastewater, including captured runoff, as a function of the characteristics of the CAFO or industry and the pretreatment of the wastewater.
2. Estimate the annual total volume of the wastewater. This presumes that the wastewater storage reservoirs are properly designed for storm water runoff and winter storage requirements.
3. Determine the annual N (product of the values of steps 1 and 2, in kg) that will be applied in the irrigations.
4. Determine the grazing or cropping systems that will be used and the preliminary estimate of the total land area to be irrigated. Estimate the crop dry matter (Mg/ha) that will be removed in a “normal” year as a function of water and nutrient availability. Estimate the total N (kg/ha) removed in the crop, as a percentage of the crop dry matter. Convert the annual N available in the irrigation water to kg/ha. Convert the volume of wastewater to mm depth for a unit land area.
5. From other chapters (Chapters 5, 7, and 8) in this book, determine the irrigation water requirements from the consumptive water use, the precipitation, the irrigation system efficiency and uniformity, and any leaching requirements. Express the irrigation water requirements as depth (mm).
6. Compare the irrigation wastewater available (mm depth for a unit land area) with the consumptive irrigation water requirement (mm). If the available water is much less than the consumptive requirement, either another water source must be developed for irrigation or the crop yields (and N removal) may need to be

revised downward to take decreased water availability into account. If the available water is much more than the consumptive requirement, then N is not the limiting factor and the system should be designed for hydraulic loading instead of nutrient loading. Additional fertilizer N may be needed.

7. Use a N balance method, such as the method presented in the next section, to compare the kg N/ha of the applied wastewater with the kg N/ha removed during the land treatment. If the N removed in the land treatment system is less than the N to be applied, either the N to be applied has to be reduced (additional pretreatment) or the N removed has to be increased (e.g., increase denitrification losses or add more land).
8. Finalize the land area to be irrigated and proceed with system hardware selection and design.

20.6.2. Nitrogen Balance

A nitrogen balance calculation is needed to determine the total land area required for irrigation with the wastewater without exceeding the agronomic rates for N removal. The total N balance is normally calculated for a unit land area on an annual basis. Procedures have been reported for the calculation of the water and nutrient balances of the application area (e.g., Loehr et al., 1979). Thompson et al. (1997) provide a listing of the computer programs that calculate manure application rates. Some of these will be adaptable to liquid application. The N input portion, N_i (kg/ha), of the N balance is:

$$N_i = 0.01 \times [(I \times I_c) + (P \times P_c)] + F + O + S \tag{20.1}$$

where 0.01 = constant of proportionality, from 10^4 L/(ha mm) × 10^{-6} kg/mg
I = effective irrigation amount reaching the plant and land surfaces, mm
P = effective precipitation amount reaching the plant and land surfaces, mm
I_c = total N concentration in the irrigation, mg/L
P_c = total N concentration in the precipitation, mg/L
F = total N content of fertilizer added, kg/ha
O = N from other sources, such as upward movement from groundwater to root zone and contribution from legumes, kg/ha
S = mineralization of immobilized N from previous years, kg/ha.

The nitrogen loss or removal portion, N_o (kg/ha), is:

$$N_o = (0.01 \times I \times I_c)(V_f + I_f + D_f) + 0.01 \times [(G \times G_c) + (R \times R_c)] + C_u \tag{20.2}$$

where V_f = fractional loss of the input N losses due to volatilization
I_f = fractional loss of the input N losses due to immobilization
D_f = fractional loss of the input N losses due to denitrification
G = percolation from the root zone to groundwater, mm
G_c = concentration of N in the percolate, mg/L
R = runoff from the application site, mm
R_c = concentration of N in the precipitation runoff, mg/L
C_u = crop N removal, kg/ha.

If N_o is equal to or less than N_i, N is the limiting factor for the loading rate. Equating N_o and N_i, and solving for I results in:

$$\begin{aligned} \mathrm{I} = [&C_u - F - O - S + 0.01 \times [(G \times G_c) + (R \times R_c) \\ &- (P \times P_c)]/[0.01 \times I_c \times (1 - V_f - I_f - D_f)] \end{aligned} \tag{20.3}$$

The maximum allowable value of NO_3-N in the percolation to groundwater, G_c, and the surface runoff of precipitation, R_c, is 10 mg NO_3-N/L.

The percolation to groundwater will not be zero for most land application systems, but is assumed to be zero in design to be on the conservative side. In some areas, the spring thaw will result in a net discharge of soil water to groundwater. In some climates, excessive precipitation will saturate the soil profile and result in a net discharge of soil water to groundwater. Site-specific evaluation of G and G_c should be based on measurements or calibrated simulation model results.

Surface runoff of precipitation may be estimated from models such as the rational method and the SCS Curve Number, among others. Nitrogen losses of 3% to 7% of the total N application were reported from Georgia for dairy wastes applied with a center pivot (Hubbard et al., 1987). At these rates, 25 to 30 kg N/ha would be removed. For a conservative design, N removal in surface runoff may be neglected. This figure is usually less than 10% of the N removal in crop harvest.

If nitrate is the limiting factor for land application of wastewater, N fertilizer will not be added. However, if P loading is a concern, additional N may be required to balance the fertility and increase yields. The contribution of N from legumes should be included in the calculation.

The precipitation climatology for the site can be obtained from a variety of sources. USEPA (1981) recommends that the design monthly precipitation be set to the 5-yr return period frequency. Alternatively, if the annual precipitation is used, the 10-yr return period should be used, distributed by month based on the ratios of average monthly to average annual precipitation. The nitrogen content of precipitation may be assumed to be 0.5 mg/L (Loehr et al., 1979).

The fractions of applied total N that are volatilized, immobilized, and denitrified are functions of the pretreatment processes, irrigation system, soil-plant environment, and land treatment system management. In the absence of site-specific values, some approximate values may be used in design. For high-strength, high-pH wastewater from CAFOs or processing plants, volatilization losses in sprinkler irrigation may approach 20% (Broadbent and Reisenaur, 1985). Volatilization losses will increase with increasing concentrations of ammonia in the wastewater. For low-strength, neutral-pH reclaimed wastewater, the volatilization losses will be near zero, but for reclaimed wastewater with low N content, hydraulic loading will normally be the limiting factor in design. For well-aerated, coarse-textured soils, denitrification may be neglected. Periodic waterlogging, fine-textured soils, and frequent irrigation promote the conditions that favor denitrification. For these conditions, denitrification losses may be as high as 40% (Broadbent and Reisenaur, 1985). Denitrification losses in the range of 15% to 25% should be used in design. Microbial immobilization losses of nitrogen will be typically in the 22 to 45 kg/ha range, but may be as high as 55 kg/ha (Broadbent and Reisenaur, 1985). For an annual irrigation application of 333 mm irrigation with a total N content of 300 mg/L, the microbial immobilization is only about 5%. Consequently, the immobilization fraction, I_f, may be neglected. The USEPA (1981) guidelines are 15% to 25% for denitrification and volatilization combined and 0% net storage in soil (immobilization and mineralization).

Nitrogen that is applied in organic form (slurry, dry manure, or suspended solids) should be taken into account in the design loading rate. About 25% to 35% of the organic N will be released in the first cropping season. For long-term application of solids, the total N content of the solids should be added to the N balance.

Net mineralization of the soil organic N is about 2% to 4% per year of the total soil N, which may be 1000 to 5000 kg/ha (Keeney, 1983). The mineralization term for a high-fertility, high-productivity land application site may be as much as 200 kg/ha. Ideally, the mineralization term could be indexed to the crop uptake term. If a harvested forage crop yield of 10 Mg/ha has a total N content of 2%, 200 kg total N will be removed in the aboveground biomass that is harvested. As a generality, there will be a corresponding 200 kg total N immobilized in organic form in the belowground biomass. Most of this will be subsequently mineralized to inorganic N in succeeding years, and could be incorporated into the design N loading rate calculation. If the net storage is assumed to be 0% of the applied N for a steady state situation, the design will be conservative (no net sink to soil organic material).

With proper application rates, annual crop uptake and harvest removal of N will be from 50% to above 90% of applied N in the year of application. The remainder is typically in non-harvested, organically bound N in plant roots and other plant residues, with contributions from other N losses. For design of loading rates at high N applications, a value between 55% and 75% N crop uptake and harvest removal should be used. The value would be a function of the crop and the soil. For forage crops, crop N uptake may be generalized as a percentage of the harvested dry matter, especially at higher N application rates. The range for design is 1% to 3% total N in harvested dry matter for forages.

For most pure perennial grass pastures on the acid soils of the southeastern U.S., the desired fertility N:P:K ratios are 4:1:2 (Chamblee and Spooner, 1985). If nitrogen is lost from the wastewater treatment and application systems, additional N may be needed to increase the uptake of P in the forages. This may be provided in supplemental fertilization or from the use of interplanted or double-cropped legumes.

The nitrogen balance equation simplifies, with the assumptions of the preceding paragraphs including no fertilizer nitrogen applied, to:

$$I = [C_u - S - 0.01 \times (P \times 0.5)]/0.01 \times I_c \times 0.75 \tag{20.4}$$

For a sample calculation, assume the input data for irrigation from a dairy CAFO lagoon, on an annual basis: The wastewater has a total N content of 300 mg/L. The effective precipitation is 1270 mm. The crop in the southeast U.S. is Coastal bermudagrass, with interplanted winter wheat, harvested as forage and removed. The total dry matter yield is 15 Mg/ha, with an N content of 1.5%, so the N removed is 225 kg/ha. The annual mineralized N (S) is 50 kg/ha. Solving for I shows the effective irrigation amount should not exceed 75 mm. If more than 75 mm irrigation water is applied, more N will be applied than can be removed by the crops. The land area required for the wastewater irrigation should be determined by the total volume of the wastewater that will be available on an annual basis.

20.6.3 Phosphorus Balance

Due to the complexity of the P chemistry of soils, similar models for P have not been developed. If the P loading is the limiting factor, the general requirement is that the total P loading should not exceed the P agronomic uptake and removal rate. The P content of the removed crops is used to determine the total land area required for the application of the wastewater.

20.7 IRRIGATION SYSTEMS USING WASTEWATER

Surface irrigation was initially used for land treatment of wastewater and irrigation with reclaimed water, because it was a method with low cost, low technology, and low capital investment. The major problems with surface irrigation are deep percolation of water containing nitrates at the head of the field and the necessity to contain and recycle the tailwater runoff from the land irrigation site (Reed and Crites, 1984). When the local conditions are favorable for gravity flow, the system may be designed as an overland flow treatment system (USEPA, 1981; Tedaldi and Loehr, 1992). Sprinkler irrigation systems, however, are the dominant systems for applying wastewater and reclaimed water, with microirrigation systems gaining in popularity.

20.7.1 Sprinkler and Microirrigation Systems for Reclaimed Water

Reclaimed water may be used for any type of sprinkler or microirrigation. The use of reclaimed water does not change the design, except for the additional safety features that must be added to protect a potable water supply. These are discussed separately in this chapter. For urban and turf uses, solid set systems with underground mains and laterals are standard. For tree, forage, and crop irrigation, the quality of the reclaimed water may exceed the quality of the nearby surface and groundwater as a result of the filtration and disinfection. Again, design of the system is the same as for other water sources.

Sprinkler and microirrigation systems have the following advantages when used for reclaimed and wastewater irrigation:

- The applications of water and nutrients are relatively uniform.
- Small irrigation applications are practical.
- With good management, there will be minimal runoff, which precludes the necessity for a runoff collection and reuse system.
- The system may be designed to minimize worker contact with the wastewater and any pathogens it may contain.
- The system may be automated to apply water to minimize public exposure to the water or irrigation water aerosols.
- The system may be automated and simplified to facilitate irrigation management by operators whose primary business is not crop production or irrigation. Examples are center pivots using dairy CAFO wastewater and subsurface drip systems for application of domestic wastewater from subsurface flow wetland systems.
- Sprinkler application of pathogens in the wastewater is effective in promoting rapid die-off, especially of viruses.
- Sprinkler irrigation will result in N losses due to ammonia volatilization, which will reduce the N loading and the potential for nitrate leaching.
- Record keeping is facilitated with the use of center pivots and other automated systems.
- With microirrigation, reclaimed water and wastewater may be applied below the ground surface to minimize human contact and runoff potential of applied constituents.

Disadvantages of using wastewater, but not reclaimed water, with sprinkler and microirrigation systems are:

- Particulate matter in the water may accumulate in mains, laterals, nozzles, emitters, and other system components. Anaerobic conditions, corrosive conditions, odors, and particulate aggregates that reduce pipe capacity and plugged nozzles and orifices may result.

- Aerosolization of the wastewater in sprinkler or sprayer irrigation may transport viruses and bacteria downwind to a distance of several hundred meters unless controlled by operating pressure and nozzle placement and design.
- Disinfection of wastewater is not an option for control of algae, iron bacteria.
- Drying periods between an irrigation and harvest are required when the wastewater contacts the plant surfaces.
- Not all crops, especially those used for human food without cooking, may be irrigated with wastewater and reclaimed water. Restrictions depend on the nature of the crop and the quality of the wastewater or reclaimed water.
- Wastewater lines and potable water lines must be separated to avoid contamination of potable water. This is also true for reclaimed water.

20.7.2 Center Pivot Systems

Center pivot systems are gaining in popularity to apply reclaimed water and wastewater irrigation due primarily to their fit into the management system, especially for managers whose primary operation is not crop production or irrigation. For a processing plant operator or a dairy manager, the center pivot is easier to manage, operate, and maintain than other sprinkler systems. When compared to a side roll (wheel line) or a big gun (gun sprinklers), the system has less reliance on skilled labor for scheduling the irrigation sets and moving the system. Record keeping is facilitated. The uniformity of water and nutrient application is also greater with the center pivot than with a big gun.

The experiences of an irrigation equipment company in the major dairy region of Texas are worthy of mention. As of 1995, the company installed 33 center pivots for irrigation of wastewater from dairies and a cheese processing plant in the Stephenville area (M. Stewart, 1995 personal communication. DeLeon Irrigation Co., DeLeon, Texas). The company also installs center pivots for row crops and forages, so has a good basis for comparison of system operation with different qualities of water. Plugging of nozzles and other system components and corrosion were the two major potential problems associated with center pivot irrigation of wastewater.

Several features of design and operation significantly decrease the nozzle plugging potential. When compared to a center pivot for row crops, the nozzle drops have a greater spacing and the nozzle diameters are larger. As an example, a recent installation has drops on a 4.5 m (17 ft) spacing, with a smallest nozzle diameter of 7.1 mm (9/32 in). The design operating pressure ranged from 135 to 170 kPa (20 to 25 psi), which is higher than a typical low-pressure center pivot system. This combination of larger nozzle diameters and higher pressure results in a system that expels most of the solids in the water. An end gun on the pivot has proven indispensable for a relatively plugging-free system. With an end gun, the velocity of flow in the entire length of lateral keeps solids from settling and accumulating or aggregating. The booster pump for the end gun occasionally picks up some trash, but the outage rates have not been excessive. Self-draining valves, one for each span, provide drainage at the end of the irrigation period. This draining and drying reduces solids accumulation and resulting pipe corrosion, development of odors, and continuous growth of microorganisms.

The source of wastewater for dairy systems should be the second stage of the lagoon system. The primary lagoon should not be used as a source of water for center pivot irrigation because of high suspended solids, greater potential for odor, and higher levels of nutrients. The pump and intake are mounted on a floating platform some distance from the shore, with an intake depth of about 0.3 m. This avoids floating and bottom solids. As a consequence of high BOD in the wastewater, the water is normally anaerobic, so algae are not a problem. The inlet pipe has a trash screen, with openings at least 12.5 mm in diameter. A separate cage of fine mesh screen for the intake is not required, nor is a filter for the system. At the end of the irrigation cycle, the inlet pipe is backflushed as water drains from the line into the lagoon. An air relief valve at the high point of the irrigation line, normally the lagoon embankment, is necessary. The design capacity of the center pivot is normally based on crop irrigation needs for the area covered, rather than on the average flow rate of wastewater. This overdesign of system capacity results in higher flow rates and greater flexibility of system operation, especially for lagoon pump-down following runoff from open lots due to heavy rains.

20.7.3 Big Gun Systems

Big gun systems are widely used in wastewater irrigation, especially when the wastewater application fields are nonuniform in shape or when tree crops or wooded areas are used for the land treatment (Yoder, 1994). Big gun systems have the advantage of large nozzle diameters, which enables pumping of slurries and wastewater with suspended solids. The high pressure of big gun systems also facilitates pumping with solids without system plugging. Filtration requirements are eliminated, but the intake pipe inlet should be screened to keep large objects out of the pump and lines. Rapid emergency pump-down of lagoons with high suspended solids is facilitated with big gun systems.

20.7.4 Microirrigation Systems

The use of microirrigation for reclaimed water and wastewater is increasing despite problems with clogging due to physical, biological, and chemical constituents in the wastewater. The potential for emitter plugging due to degraded water quality is the major concern for microirrigation with reclaimed water (Hills and Tajrishy, 1995). The high quality of reclaimed water that has had tertiary treatment and disinfection is very compatible with microirrigation systems. However, virtually all agricultural wastewater and most municipal wastewater with only secondary treatment have too high an organic matter content (high BOD and TSS) for chlorination or other disinfection to be practical. Chlorination of high-strength organic material in water is known to produce carcinogenic substances, so high doses of chlorine are not a feasible solution. Consequently, microirrigation with emitters is generally limited to reclaimed water or low-strength secondary wastewater from reservoir storage. Microsprinklers, microsprayers, bubblers, and other large-orifice forms of microirrigation could be used if the water is adequately filtered. Hills and Brenes (2001) concluded that drip tape appears to be suitable for use with effluent from a secondary clarifier after chlorination and filtration with a silica sand no. 20 filter and 105-μm screen filter at each manifold. Periodic chlorination, ideally with a clean water source and flushing, would still be required to control growth of biological films and slimes.

20.7.4.1 Subsurface drip systems. Subsurface drip irrigation will pose less threat of pathogen contamination (Phene and Ruskin, 1995; Trooien et al., 2000), but may be more difficult to manage. Gushiken (1995) lists the following advantages of subsurface drip irrigation with reclaimed water: (1) minimizes health risks; (2) minimizes liability exposure associated with overspray and aerosol drift near residential properties; and (3) eliminates odor, ponding, and runoff, in addition to the other advantages of subsurface drip irrigation over other forms of irrigation.

When subsurface drip irrigation was used in a high-frequency mode in a California study, minimum leaching of nitrate occurred (Phene and Ruskin, 1995). The four recommended conditions are: (1) irrigation events are short and frequent and designed to replace crop water uptake as closely as possible (no leaching); (2) nitrogen is applied through the system at a rate equivalent to the crop uptake rate less the amount mineralized from the soil; (3) the crop is deep rooted; and (4) the water table is at least 2 m from the soil surface (Phene and Ruskin, 1995).

Oron et al. (1992) studied drip irrigation (surface and subsurface) of cotton, alfalfa, sweet corn, and wheat with secondary wastewater in Israel. They noted no technical failures if proper filtration was done. No contamination of agricultural products with microbes was detected. Subsurface drip irrigation for home landscapes is increasingly used for effluent from household septic systems when subsurface constructed wetlands are incorporated into the design. The wetlands remove the suspended solids that otherwise rule out microirrigation systems for wastewater.

20.7.4.2 Emitter plugging. Two approaches are used to reduce clogging: improved emitter design and pretreatment of water used for microirrigation (Hills and Tajrishy, 1995). The improved emitter designs include turbulent-flow labyrinth or self-cleaning types. Treatment for reclaimed water is primarily filtration, followed by disinfection with chlorine or an equivalent oxidant, or exposure to ultraviolet light. Hills and Tajrishy (1995) state that filtration followed by UV disinfection and chlorination may be necessary to produce water with an acceptable bacterial count for microirrigation of fresh market produce. Filtration alone is not sufficient to eliminate the clogging potential (Adin and Sacks, 1991; Hills and Tajrishy, 1995). In addition, filtration of wastewater from storage reservoirs results in the need for very frequent backflushings (Ravina et al., 1995), which interrupts the irrigation and creates a disposal problem.

Municipal effluent from a secondary clarifier in California was examined for plugging potential in a microirrigation system by Hills and Tajrishy (1995). Combinations of filtration (silica sand no. 20 or 150-mesh (100-μm) screen) and disinfection were used with turbulent labyrinth and self-flushing in-line emitters. Their conclusions were: (1) Chlorine (or equivalent disinfection) is necessary to prevent growth of bacterial slimes and algae within microirrigation systems using reclaimed water. (2) Filtration alone with either media or screen filters does not prevent clogging. (3) Adequate filtration with granular media filters will reduce the chlorination requirement and frequency of line flushing. (4) Intermittent chlorination of 2 mg/L free residual chlorine during the last hour of an irrigation cycle is as effective as continuous chlorination of 0.4 mg/L for preventing biological film formation and emitter clogging. (5) UV disinfection alone does not prevent clogging of emitters. The self-flushing emitters required granular media filtration and chlorination to maintain high uniformity, but either media or screen filtration with chlorination was sufficient for the labyrinth turbulent flow emitters.

In a study of microirrigation with filtered wastewater from a reservoir in Israel, Adin and Sacks (1991) reached the following conclusions: (1) Clogging of inline emitters is caused primarily by suspended solids, but they do not necessarily initiate the clogging process. (2) Sediment buildup begins with deposition of amorphous biological films, to which other particles adhere. (3) Algae cause emitter clogging only when attached to other particles. (4) Filtration prevents immediate clogging by large or irregular-shaped particles. (5) Clogging potential may be reduced by chemical pretreatment with oxidants and flocculants or by modifying the internal emitter design.

Labyrinth long-path emitters were much more prone to clogging than a self-regulating emitter. In an earlier study, Adin and Elimelech (1989) reported that screen filters (80- and 130-µm polyester) performed very poorly, with only a few percent particle removal, with wastewater from a storage reservoir. Deep-bed granular media filters (effective grain sizes of 0.7, 0.9, and 1.2 mm) removed 30% to 70% of the suspended particles.

Juanico et al. (1995) examined effects of adding municipal wastewater effluent to a shallow, freshwater reservoir in Israel. They noted that the addition of effluent very quickly (within 2 wks) and very dramatically (by a factor of 2 to 4) increased the clogging capacity of the water on an 80-µm micron mesh screen filter. This was primarily due to an increase in large plankton species (cyanophytes, rotifers, and crustaceans). Sagi et al. (1995) identified a colonial protozoa (*Epystilys balanarum*) and sulfur bacteria (*Beggiotoa alba*) as the major sources of clogging of emitters in Israel. In addition to accumulation on all components of the system, these organisms produced a film or slime that enhanced the accumulation of other particles. The sulfur bacteria were present only in water containing hydrogen sulfide (H_2S) and oxygen. Both are controlled by chlorination, but not by filtration.

20.7.5 System Components

Pumps selected for wastewater irrigation systems are generally centrifugal, powered by electric motors (Sneed, 1991; MWPS, 1993). The procedures for determination of the total dynamic head are the same as for pumping of first-use water. Pump flow capacity is normally determined by the volume or flow rate of the wastewater. An exception will occur when dewatering of a lagoon is specified by regulation. For example, Texas regulations require the CAFO lagoon be pumped to the permanent marker (top of the design operating volume) within 21 days whenever the lagoon level reaches or exceeds a level corresponding to one-half of the design runoff volume (TWC, 1990; TNRCC, 1994). Natural Resources Conservation Service (NRCS) guidelines for the design capacity of the pump are based on three limitations: no pumping at night, no pumping during rainfall, and no pumping to saturated ground except when necessary to protect the lagoon from overtopping. This simplifies, with assumptions, to an informal NRCS guideline that the pump capacity should be sufficient to pump the storm runoff from a 24-hour, 25-year precipitation event on the area of the CAFO within 10 days, with the pump operating 10 h/day (K. Schrunk, 1994 personal communication, NRCS Area Office, Stephenville, Texas). Pumps sized according to this guideline will determine the desired capacity of the irrigation system. The pump will be overdesigned for normal wastewater generation rates. In practice, when N loading is the limiting design factor, the irrigation system may be in operation only a few days per month under normal or below-normal precipitation conditions.

The solids content of the wastewater has to be taken into account in the component selection. In general, sprinkler irrigation systems can be used with wastewater solids content up to 4% without affecting system design (MWPS, 1993). For higher solids content, specialized equipment is needed. Open-impeller centrifugal pumps can handle liquids with up to 15% solids, especially when the pump has a cutter blade at the inlet

(MWPS, 1993). The pumps with cutter blades (trash pumps) are compatible with big gun sprinkler systems, but care should be taken to ensure that the system has sufficient pressure. If the wastewater has more than about 1% solids, an experienced design engineer should be consulted (Sneed, 1991).

Filters will be needed for microirrigation with wastewater. An experienced design engineer should be consulted for filtration system selection.

20.7.6 System Pipeline Operation

Several general guidelines to minimize problems with system operation are apparent. Thermoplastic (e.g., PVC) system components will minimize corrosion problems, but may increase problems associated with algal growth in the lines. PVC pipes for aboveground operation would need to have ultraviolet light protection. The irrigation lines should be drained or flushed with high-quality water after irrigation to avoid corrosion in metal lines and development of odors in any lines. The major problems occur with solids that settle and develop anaerobic conditions. The nutrient content of the wastewater promotes the growth of algae, bacteria, and protozoa that may cement the solids and restrict pipe capacity. Hydrogen sulfide gas as a product of anaerobic digestion in pipes will collect at high points in the pipe line. A metal pipe without air release valves at high points is especially susceptible to corrosion (SCS, 1983; Wescot and Ayers, 1985).

20.8 DESIGN AND OPERATION OF SYSTEMS TO PROTECT HUMAN HEALTH

Design and operation of reclaimed water and wastewater systems for areas with public access require special attention to protect human and animal health. General guidelines are contained in a U.S. Golf Association guide (USGA, 1994). Although these guidelines were written for reclaimed water use in areas with public access, most are also applicable to irrigation with wastewater. The regulations of each state or country should be reviewed for compliance.

Precautions to take to avoid or decrease the health risk of irrigation with reclaimed water and wastewater are:

- Humans and animals should not be allowed in application fields that are being sprinkler irrigated with wastewater or reclaimed water. Turf, forage, and other vegetation should be allowed to dry completely following irrigation before human entry is allowed into the area. Irrigations should be applied in cycles, with each irrigation followed by several days of non-irrigation.
- Sprinkler systems should not be operated at night or during periods of rain to reduce the possibilities of direct runoff. Runoff of wastewater should not be allowed to enter surface water sources.
- Irrigation with systems that minimize exposure of humans, animals, or food crops to the wastewater should be considered for areas with high potential for traffic or disease. Workers in direct contact with wastewater should change clothing and wash thoroughly after contact with the wastewater.
- To reduce aerosol formation, irrigation systems should have a low operating pressure and a low height of application. A buffer zone should be established between the sprinkler irrigation site and areas with public access. Sprinkler or spray irrigation should be applied during periods with good vertical dispersion, rather than lateral dispersion, which could carry aerosols downwind.

- All agricultural and municipal water of runoff origin should be considered to have indicator bacteria counts higher than the primary contact standard, unless water quality analyses indicate otherwise.

To protect against cross connection with potable water lines:

- Use a minimum of a reduced-pressure principle backflow device at the service connection of the potable water system.
- Include a double check-valve assembly for any dedicated potable water supply for fire protection.
- Include an air-gap separation assembly for potable water lines connected to lake or pond fill lines.
- Remove all physical connections between the reclaimed water system and the potable water system.
- Do not use common trenches for potable water and reclaimed water lines and do not allow unknown lines in a retrofit.
- The reclaimed water system should have lower pressure than the potable water system.
- Maintain a separation between reclaimed water lines and potable water lines. These requirements may vary from state to state. The minimum separation for parallel lines should be 3.0 m, with 1.2 m for special circumstances. The reclaimed water line should be 0.3 m deeper than the potable water line. When lines cross, the reclaimed water line should be at least 0.3 m below the potable water line.
- Potable and wastewater lines should not be connected or have a possibility of being connected.
- Reclaimed water lines should be protected against unanticipated uses by the public. Special quick-coupler valves or special tools for access to the reclaimed water line are recommended. No reclaimed water lines should have hose bibbs.
- The clean water source for flushing of wastewater lines after use should be protected against backflow or contamination.

All onsite irrigation and potable water wells should be protected. A concrete slab extending 3.0 m in all directions is recommended. Drinking fountains should have special, self-closing covers to protect them from spray from sprinkler irrigation systems using reclaimed water.

All reclaimed water lines, valves, and other equipment should be clearly marked. Reclaimed water lines should be a different color or color pattern (e.g., stripes) than potable water lines. Purple is the preferred color. Warning signs should be numerous and conspicuous, preferably with a purple background. For example, golf score cards and other printed material should contain appropriate warnings.

Install low-pressure sensors with the irrigation system controller to shut the system down in the event of uncontrolled discharge from a pipe or nozzle break. Incorporate valves for flushing at low elevations and at the end of lines. Incorporate valves for air relief at high locations on the lines.

Depending on the concentration of suspended solids in the reclaimed water lines, use dirty-water valves and nozzles that are less prone to clogging (e.g., impact nozzles instead of gear-driven or valve-in-head nozzles). If the reclaimed water is high in salinity, avoid the use of dissimilar metals in the system components.

If storage of reclaimed water is necessary, use storage tanks instead of reservoirs. If the reclaimed water is stored in a reservoir, filtration at the intake will likely be needed. Consider a primary screen of 10- to 30-mesh at the source inlet, a media filter for algae and other suspended solids, and a stainless steel screen filter if a microirrigation system is used. Design on-site storage reservoirs for wastewater irrigation to minimize potential problems with weeds, algae, odors, aesthetics, and health hazards. When possible, the flow of fresh influent into the irrigation reservoir should be terminated during the irrigation period to prevent short circuiting. Mechanical agitation or other source of turbulence for the irrigation reservoir should be avoided during the irrigation, except for the special case of infrequent sediment or sludge removal, which requires special equipment and precautionary measures regarding crops, timing, rates, and runoff control practices. Include aeration and oxidation features for reclaimed water reservoirs and water features that collect runoff from the land application site. These features include fountains, waterfalls, constructed wetlands for algal oxidation, and air injectors. On-site reclaimed water storage reservoirs should be protected against public access unless the water meets USEPA primary contact standards for bacteria.

Use a dual irrigation system (i.e., two irrigation systems with separate water sources) if the reclaimed water contains anions or other constituents that could adversely impact growth or appearance of ornamental plants, golf course greens and tees, and other sensitive plantings. This is especially necessary when the wastewater treatment plant is down for maintenance or if the delivery times are unreliable. If the reclaimed water or wastewater is of poor quality, blending with fresh water will help in controlling total dissolved solids, total suspended solids, and BOD.

20.9 MONITORING

There are two types of monitoring requirements. The first is more or less standard monitoring procedures to determine if the irrigation system is operating within design specifications. The second is monitoring to determine if the land treatment system is operating within design specifications, with an emphasis on protection of human health (Westcot, 1997). Monitoring for irrigation system performance is adequately covered in other sections of this monograph, so the focus here will be on monitoring for land treatment performance. This may be divided into two categories: compliance monitoring and process monitoring (Reed and Crites, 1984). Monitoring for compliance should include the details of the sampling in a quality management plan (Wescot and Ayers, 1985). Assistance with development of the plan may be obtained from the NRCS, the Cooperative Extension Service, a state or federal water quality agency, and/or a consulting engineering firm.

20.9.1 Compliance Monitoring

Compliance monitoring for nutrient content of surface runoff, nutrient content of soil water percolating to groundwater, nutrient loading, and hydraulic loading may be under the purview of appropriate state and federal agency guidelines and regulations. Records may be required. Considering the dynamic nature of guidelines and regulations and the variations in different jurisdictions, this section is not to be construed as an authoritative source on monitoring requirements. Consult the NRCS, state extension waste management specialists, consulting engineers, and state and federal environmental protection or natural resources agencies. Record keeping is generally the responsibility of the operator or manager of the land treatment system.

20.9.2 Process Monitoring

Process monitoring for land treatment of wastewater serves the following purposes (USEPA, 1981; Westerman and King, 1983): to verify system performance relative to loading rate, environmental impact, and treatment effectiveness; to determine degradation of soil, groundwater, and surface water; to assess the vegetation-soil system to ensure that viable vegetative cover is maintained and that vegetation management is effective; to determine safety of use of harvested or grazed vegetation; to monitor wastewater generation rate and composition for significant changes that would impact system operation; to monitor effectiveness of treatment processes prior to land application of reclaimed water or wastewater; and to determine needs for subsurface drainage systems, soil amendments, additional nutrients, or other corrective actions.

20.9.3 Soils

Some of the soils data needed for design of the land treatment system will also serve as baseline information for the monitoring program. If the wastewater has constituents that will be removed by soil treatment, the soil information will also serve as a baseline. The soil background data that may be needed for baseline include: texture, structure, and profile; infiltration rate and permeability; soil horizontal and vertical variations that would impact land application; background phosphorus and nitrogen content, with special emphasis on the various types of phosphorus; heavy metals content; calcium, iron, and aluminum content and forms, if phosphorus loading is at a rate that exceeds crop uptake and removal; chemical properties of soil and soil water, including CEC, pH, total salinity or conductivity, specific anions, SAR, COD, Eh, alkalinity, and phosphorus sorption capacity; organic matter; groundwater levels (which may be seasonal) and gradient; and groundwater chemical constituents and properties, if the groundwater is shallow enough to be a factor in land application (these include nitrate and other forms of nitrogen, anions, pH, Eh, COD, phosphorus, alkalinity, organic carbon, and metals including calcium, iron, and aluminum).

20.9.4 Groundwater and Vegetation

In some cases, groundwater should be monitored periodically during operation of the land treatment/irrigation system. Monitoring wells should be located up-gradient, on site, and down-gradient if the soil profile to groundwater is permeable and the potential exists for groundwater contamination. Careful site selection and the use of well casings are important to avoid contamination. George et al. (1987) is an excellent reference for the design of a groundwater monitoring program for a site impacted by excessive loading.

Sampling of vegetation should be included in a monitoring program. Vegetation variables of interest are yield and/or total dry matter removed by harvest and nutrient content, especially total nitrogen, nitrate, and phosphorus. The sampling interval for monitoring vegetation is normally at harvest. Harvest dates and yields should be recorded, with nutrient content recorded if available. Pre-harvest sampling is appropriate when the vegetation is to be grazed or harvested for forage at times when the nitrate content may be high enough to be toxic to livestock. These conditions primarily exist for cereal grain and corn crops with high nitrogen fertility during conditions that favor low photosynthetic rates (cool, cloudy weather and low soil moisture) (Heath et al., 1985). An agronomist should be consulted to provide details of the appropriate forage or crop sampling program.

20.9.5 Water

A suggested protocol for wastewater monitoring will include samples of the following constituents and properties at influent and effluent locations: nitrogen forms, such as organic, total Kjeldahl, ammonium, and nitrate; phosphorus forms, such as orthophosphate, organic, inorganic, bioavailable, and iron oxide strip reactive; sodium, calcium, and magnesium for SAR or ESP calculation; electrical conductivity and total dissolved solids; Eh, pH, and dissolved oxygen; trace (heavy) metals; alkalinity; BOD and/or COD; total dissolved and suspended solids, with separation into volatile and fixed fractions; pathogens or indicator organisms if the wastewater application is in an area with public access; oil and grease if the wastewater is from a municipal or processing source; total organic carbon (TOC), depending on wastewater source; and volatile organic compounds (VOC), depending on wastewater source.

20.9.6 Monitoring Frequency

The frequency of the monitoring program depends on the size of the system and the potential impact of any variations on system operation. The frequency of compliance monitoring will be established by the regulatory or permitting agencies. Process monitoring frequency for wastewater should be at least quarterly, with annual monitoring of forage, soil, and groundwater variables (Reed and Crites, 1984). Significant variations in loading or flow may dictate sampling on a more frequent basis. Water levels in lagoons, ponds and reservoirs used for storage of reclaimed water or wastewater prior to irrigation withdrawal should be measured at least weekly. Precipitation form and amount should be measured daily.

Monitoring at the application site may also be required by regulatory or permitting agencies. Times and amounts of irrigation should be recorded. Ideally, the basis for irrigation scheduling, such as soil moisture depletion and evapotranspiration rate, will be monitored and recorded. However, this is not practical for many wastewater application locations and operations. Supplemental fertilizer formulations and rates should be recorded. Solid waste or slurry application and commercial fertilizer application, if any, on the wastewater irrigation site should be recorded.

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